A Generic Framework for the Design Optimisation of Multidisciplinary UAV Intelligent Systems using Evolutionary Computing

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This paper describes the formulation and application of a design framework that supports the complex task of multidisciplinary design optimisation of Unmanned Aerial Vehicles (UAVs). The framework includes a Graphical User Interface (GUI), a robust Evolutionary Algorithm optimiser, several design modules, mesh generators and post-processing capabilities in an integrated platform. Traditional deterministic optimisation techniques for MDO are effective when applied to specific problems and within a specified range. A new class of optimisation techniques named Hierarchical Asynchronous Parallel Evolutionary Algorithms (HAPEAs) have shown to be robust as they require no derivatives or gradients of the objective function, have the capability of finding globally optimum solutions amongst many local optima, can be executed asynchronously in parallel and adapted easily to arbitrary solver codes without major modifications. The application of the methodology is illustrated on multi-criteria and multidisciplinary design problems. Results indicate the practicality and robustness of the method in finding optimal solutions and Pareto trade-offs between the disciplinary analyses and producing a set of non dominated individuals.

Nomenclature

UAV	=	unmanned aerial vehicle
C_p	=	pressure coefficient
C_d	=	drag coefficient
C_l	=	drag coefficient
t/c	=	thickness-to-chord ratio
Cm	=	pitching moment coefficient
W_{SC}	=	wing structural weight
AR	=	wing aspect ratio
λ_{br}	=	taper ratio root to break
λ_{bt}	=	taper ratio break to tip
Λ	=	wing 1/4 chord sweep
b_l	=	break location

I. Introduction

THE use and development of UAVs for military and civilian applications are rapidly increasing but there are difficulties in the design of these vehicles because of the varied and non-intuitive nature of the configurations and missions that can be performed. Similar to their manned counterparts, the challenge is to develop trade-off studies of optimal configurations to produce a high performance aircraft that satisfy mission requirements. The goal of this study is to address these issues from a multi-criteria and multidisciplinary design optimization (MDO) standpoint.

Traditional methods for solving an MDO problem use gradient based optimization techniques[1-6]. These techniques are effective when applied to specific problems and within a specified range and efficient in finding optimal global solutions if the objective and constraints are differentiable. Robust and alternative numerical tools are required if a

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broader application of the optimiser is desired or if the complexity of the problem arises because it is multi-modal, involve approximations, is non-differentiable or involve multiple criteria and physics.

An emerging technique for optimization is Evolutionary Algorithms (EAs)[7, 8]. EAs are based on Darwinian evolution; whereby populations of individuals, which represent the design variables, evolve over a search space and generate offspring by the use of different mechanisms such as mutation, crossover and selection. An attractive feature of EAs is that they evaluate multiple populations of points and are capable of finding a number of solutions in a Pareto set. EAs have been successfully applied to different aircraft, wing, aerofoil and rotor blade design and optimization problems[9-12]. One major drawback of EAs is that they are slow in converging, as they require a large number of function evaluations to find optimal solutions and have poor performance with increasing number of variables. Hence the continuing effort has been on developing robust but faster numerical techniques to overcome these challenges and facilitate the complex task of design and optimization in aeronautics. In this work we describe the design and implementation of a framework for the design and optimization of aeronautical systems. This framework uses a robust evolutionary technique, which is scalable to preliminary design studies with higher fidelity models for the solution and is applicable to the design and optimization of UAV systems.

The rest of the paper is organized as follows, section 2 summarizes some requirements for a robust framework for multi-criteria and multidisciplinary design optimization, section 3 describes the design characteristics of the proposed framework, and implementation of the framework is presented in section 4. Section 5 illustrates the application of the method for real world problems. Finally section 6 provides summary and future directions for the research.

II. Requirements for a Multi-Criteria Multidisciplinary Design Optimization Framework

Complex optimization problems in engineering may involve non-linearities, multi-criteria and multidisciplinary considerations. In order to handle these complexities it is desirable to develop of a system, which facilitates integration of a series of design and analysis tools, graphical user interfaces (GUI) and post-processing capabilities. This section focuses on the requirements, development and implementation of such a framework using Evolutionary Algorithms in which different multidisciplinary and multi-criteria problems can be analysed. The fundamental idea with the framework is to simplify the task of integration to the design team so that it can focus on the problem itself. The idea on the development of this framework is a generic system that can be easily developed, maintained and extended.

The basic requirements for a MDO framework can be subdivided in architectural design and information access, optimization methods, problem formulation and execution[13-15]. In *Architectural Design* some of the considerations are that the framework should be developed using object-oriented principles, provide an easy to use and intuitive GUI, be easily extensible to integrate new processes and numerical methods into the system, not impose unreasonable overhead on the optimization process handle large problem sizes and be based on standards.

Information Access refers to the *framework* on providing facilities for database management, capabilities to visualize intermediate and final result from the analysis or optimization, allow capabilities for monitoring the status of an execution and mechanisms for fault tolerance. On *Optimization Methods*, the framework should allow ease of integration of robust optimization tools, allow an easy coupling of different disciplinary analysis with optimizer, provide schemes for sub-optimizations within each design module and allow the user to incorporate legacy codes which can be written in different programming languages and proprietary software where no source code is available. A final consideration is on *Problem Formulation and Execution* where the framework should allow the user to configure and reconfigure different multi-criteria and MDO formulations easily without low level programming, allow the execution and movement of data in an automated fashion, should be able to execute multiple processes in parallel and through heterogeneous computers and execute different optimization runs in a batch mode. In the following sections we will describe how the framework satisfies these requirements.

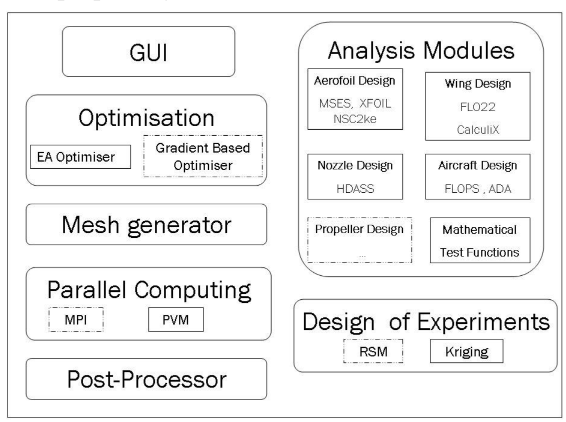

Figure 1. MDO Framework

III. Design

With these requirements in mind the general scope for the framework was identified. The framework was designed to address all of these requirements to some extent. Figure 1 shows a representation of different components. The framework has a GUI, a robust optimization tool, several analysis modules and capabilities for parallel computing, mesh generation, Design of Experiments (DOE) and post-processing.

IV. Implementation

Integrating these components is a complex task. This work considers the development of the architecture, the GUI, implementation and extension of a robust optimization tool, a general formulation for MDO and multi-criteria problems, and capabilities for pre and post-processing. The DOE capability has been accounted for, but has been evaluated only for simple mathematical test cases. The following sub-sections detail how the requirements are satisfied.

A. Architectural Design and Information Access

To satisfy the architectural design requirements the platform uses an object-oriented approach in C++. The benefits of using object-oriented software are the ease of implementation and extension of software in a modular fashion by the use of classes and methods. In an industrial and academic environment the need for a user-friendly application is required hence a simple GUI was designed. There were many considerations and options for the GUI development, but knowledge in C++ and the use of object-oriented principles were the main considerations. The Fast Toolkit (FLTk) library[16] was selected for this task. This toolkit provides a friendly and easy to use environment for different implementations. The GUI is simple and modular on its implementation and consists of five main modules as illustrated in Figure 2. The main modules are: Design and Analysis, Design of Experiments, Post-processing and Parallel Processing. The GUI facilitates development, extension and modifications of modules in a rather simple manner. The user has to create only a few subroutines within the corresponding module.

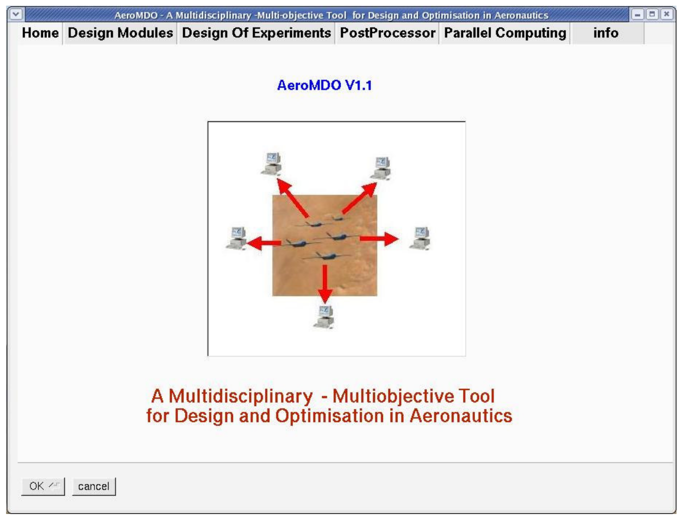

Figure 2. GUI Sample

1. *Design and Analysis Module*

As illustrated in Figure 3 the Design Module allows the user to conduct a single design and optimization for different aeronautical applications and mathematical test cases. So far this module contains five sub-modules for aerofoil, multi-element aerofoil, nozzle, wing, aircraft and mathematical functions design or optimization. As designed the framework is flexible and provides for ease of implementation of other design modules. Modules currently under development are such as those for propeller, cascade aerofoil and rotor blade design.

2. *Development of Aeronautical Design Modules*

Before implementing a sub-module it is necessary to develop a design module interface, this comprises a series of files written in C++ that allow communication between the GUI, analysis codes, the optimizer and the parallel processing capability. When designing the interface a choice has to be made depending if the source code for the analysis tool was available or not. In the current implementations minimal modification to the source code was required, ideally it is desirable to operate only through the input/output files of the analysis tool. In the implementations considered, a design template was used in conjunction with one or two additional files which contain the necessary linking subroutines allowing a rather fast implementation of the design modules. So far, there are subroutines for aircraft, nozzle, wing and full aircraft configuration design. Each of these options allows the user to perform a single design analysis or a full optimization. A general algorithm for the implementation of a new design module is represented in algorithm 1.

While Stopping condition not met ;; //Infinite loop

Receive information from optimizer: $O:O \rightarrow X, g_i, D$ // *X* Design variables, constraints (g_i) and Aerodynamic Data (*D*)

Generate Geometry: $G = f(X)$, $G =$ (aerofoil, wing nozzle, aircraft shape)

for i=0,n // N Number of objectives

Evaluate: $\Im(G, g_i, D)$ // Analyse candidate geometry

Check for convergence

Calculate fitness: $f_i = f(\Im(G, g_i, D))$

Return the computed individual (Design variables + fitness vector to optimizer): $X + f_i \rightarrow O$

end loop

Algorithm 1. Design Modules Algorithm

Aerofoil Design and Optimization Module: This module allows the user to perform a single analysis or a full

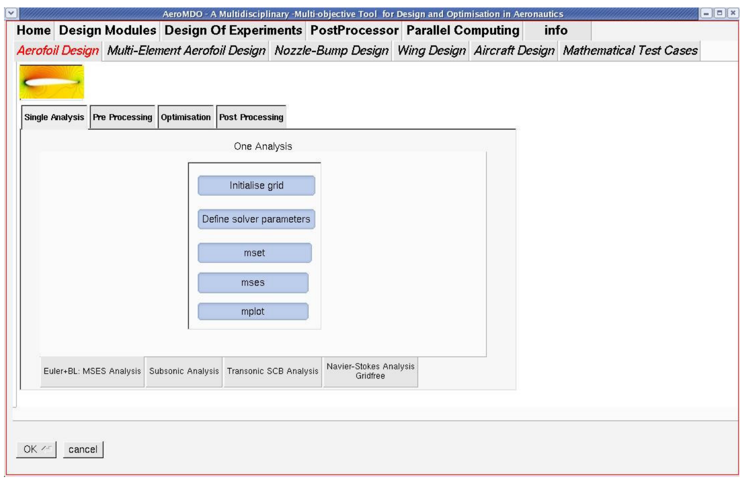

Figure 3. Aerofoil Design and optimization module

aerofoil optimization routine. Three different CFD codes at a combination of them can be used: A panel method (XFOIL)[17], an Euler + boundary layer (MSES)[18] or Navier-Stokes analysis (NSC2ke[19]). Figure 3 illustrates this. Details on the analysis tools used in this module and its applications are presented in section 5.

Wing Design and Optimization Module: This module allows the user to conduct a single analysis on a wing or an optimisation study. These could be studies in one or several objectives or with multiple disciplines. Figure 4

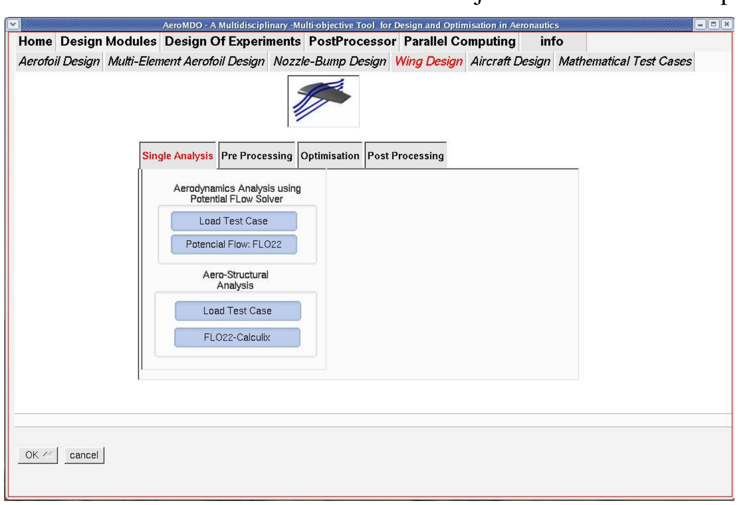

Figure 4. Wing Design and Optimisation Module

illustrates this module. Details on the analysis tools used in this module and its application to multi-criteria and multidisciplinary wing design are presented in section 5.

Aircraft Design and Optimization Module: This module allows the user to analyse and optimize different problems related to aircraft external configuration design. It can be used to design and optimize different subsonic, Unmanned Aerial Vehicles, transport or supersonic aircraft. Single or multi-criteria optimization studies can be performed. Comparison of different multi-criteria analysis such as Pareto optimality and Nash equilibrium approach are possible. Figure 5 illustrates this module. The user can select from two different analysis codes: An object-oriented Aircraft Design and Analysis Software (ADA) developed by the first author or using the Flight Optimisation System (FLOPS) software developed by A. McCullers at NASA Langley. ADA is conceptual design and analysis software written using object-oriented principles and is based on the formulation described in Raymer[20]. FLOPS[21], a more robust solver, is a workstation-based code which has capabilities for conceptual and preliminary design and evaluation of advanced concepts. The sizing and synthesis analysis in FLOPS are multidisciplinary in nature. It has a numerous modules and analysis capabilities for takeoff, performance, structural, control, aerodynamic and noise. This code is used in some universities as well as aerospace firms and government for MDO development and it

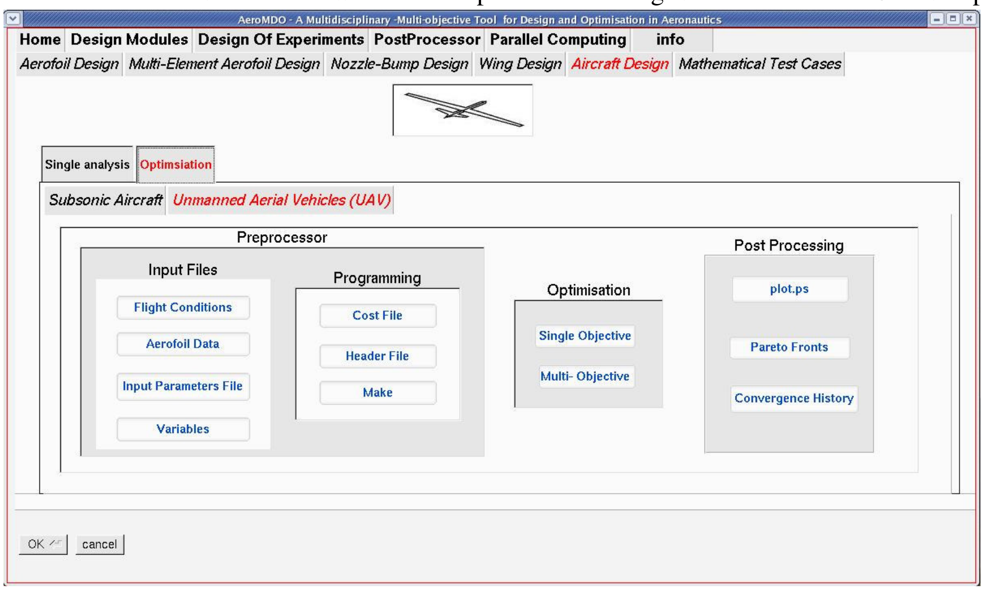

Figure 5. Aircraft Design Module

allows an integral multidisciplinary analysis for the entire aircraft mission and calculation of performance parameters such as range, endurance, takeoff field length and landing field length.

Multi-element Aerofoil Design and Optimization Module: Similar to the aerofoil design module, it allows the user to perform a single analysis or a full optimisation, the user can choose from an Euler or Navier-Stokes analysis.

Nozzle-Bump Design and Optimization Module: The Nozzle -Bump design module allows a single two-dimensional analysis or optimization using the CUSP solver developed by Srinivas[22].

Mathematical Test Functions Module: This module allows the user to design, and evaluate single, or multi-criteria mathematical test functions which give confidence in the robustness and performance of the optimization method before deciding on its application to real world problems. The current implementation includes mathematical test function for single or multiple criteria, constrained optimization, DOE and non-linear goal programming problems.

3. Design of Experiments Module

In the implementation considered in this research, the designer uses an EA for the optimization, but as discussed in section 1, one of the drawbacks of EAs is that they suffer from slow convergence. By providing a DOE capability into the framework we wish to hybridize the desirable characteristics of EAs and surrogate models such as RSM to obtain an efficient optimization system. Within this context, the DOE samples a number of design candidates at which the analysis code (CFD will run), the surrogate model is then constructed for the computationally expensive problem. Different sampling and DOE strategies can be used; Latin hypercube, Response Surface Methods or DACE/Kriging. There is sufficient literature and software developed specifically for DOE, after a careful selection of software packages it was decided to implement the DACE tool box[23] which is robust and allows different options for sampling strategies and DOE. This software was ported to Octave (a mathematical package common in most

UNIX installations) and then integrated with the framework. If desired, the user can design and implement different DOE methods.

4. Parallel Computing Module

One of the drawbacks of EAs is slow convergence but this module allows the users to dynamically create, add or delete nodes on the parallel implementation. Recent work on multi-criteria parallel evolutionary algorithms has allowed significant performance and robustness gains in global and parallel optimisation[24, 25]. The framework considers the implementation of a cluster of PCs, wherein the master carries on the optimization process while remote nodes compute the solver code. The message-passing model used is the Parallel Virtual Machine (PVM)[26].

5. Post Processing

The approach considered for post-processing was to use a combination of visualization capabilities within each analysis software, and the use of GNU plot (a graphics software common in most UNIX installations). Common to all design modules is visualization of the evolution progress of the fitness function and Pareto fronts for multi-criteria problems. Post-processing tools on each analysis module include a top view of the wing plan forms and a general 3D view of the resulting aircraft configurations. Visualization tools within each analysis software module include the pressure coefficient distribution on the aerofoil using an Euler + Boundary Layer solver or pressure or Mach contours using a Navier-Stokes solver. Examples of some visualization capabilities are presented in section 5.

B. Optimisation Methods

The second requirement is the incorporation of robust optimization tools. In this research we used and extended the Hierarchical Asynchronous Parallel Evolutionary Algorithm (HAPEA) approach developed by Whitney[27, 28]. The foundation of this algorithm lies on traditional evolution strategies and incorporate the concepts of multi-criteria optimisation, hierarchical topology, parallel computing and asynchronous evaluation. Details on the algorithm can be found in Whitney et al[27], Gonzalez et al[29, 30].

1. Implementation of Different Legacy codes

The framework also implements legacy codes in different programming languages C, C++, Fortran 90, and Fortran 77. The optimiser has been successfully coupled with the following aerodynamic and analysis software: FLO22[31], FLOPS, ADA, XFOIL, MSES, CalculiX[32] and NSC2Ke. One of the benefits of using an Evolutionary optimizer is that EAs require no derivatives of the objective function. The coupling of the algorithm with different analysis codes is by simple function calls and input and output data files.

C. Problem Formulation and Execution

A third requirement is on how to incorporate different multi-criteria and MDO formulations. There are many strategies proposed for multi-criteria and MDO and the development of these optimisation methods, architectures and decomposition methodologies has been an active field of research. The framework developed in this research is applicable to an integrated analysis or distributed MDO analysis[1-4]. Examples on the application of the method for these formulations are presented by the optimizer in section 5. The framework also satisfies the requirement of multiple executing processes in parallel; different candidate members of the population can be sent to remote parallel heterogeneous computers. Once a solution is computed it is returned to the optimiser and framework for database storage, manipulation.

V. Applications

The framework has been used to evaluate several real world problems including inverse and direct problems for aerofoil, high- lift aircraft system, multidisciplinary and multi-criteria wing and aircraft design and optimization problems[27-30]. In the following we illustrate the application of the method for three real world examples; two test cases related to UAV aerofoil design and one test case related to UAV wing design.

A. Two Objective UAV Aerofoil Section Design

In this case we consider the detailed design of a single element aerofoil for a low-cost UAV application for this case; we use the aerofoil design module. There are two subsonic design points that are considered for optimization; one for loitering flight and another for rapid-transit flight.

1. Design Variables

The aerofoil geometry is represented by the combination of a mean line and thickness distribution, which is very common concept in classical aerodynamics[33]. Both lines are represented by Bézier curves with leading and trailing edge points fixed at (0.0,0.0) and (1.0,0.0) respectively, and a variable number of intermediate control points whose x-positions are fixed in advance and whose y-heights form the problem unknowns. In this case we take four free control points on the mean line and five free control points on the thickness distribution.

2. Fitness Functions

The two fitnesses to be optimized are defined as minimisation of drag (Cd) at transit and loiter conditions.

$$\min(f_1): f_1 = c_{d_{Transit}} \rightarrow M_\infty = 0.60, \mathrm{Re} = 14.0\times10^6 \tag{1}$$

$$\min(f_2): f_2 = c_{d_{Loiter}} \rightarrow M_\infty = 0.15, \mathrm{Re} = 3.5\times10^6 \tag{2}$$

3. Design constraints

The thickness of each aerofoil must exceed 12% ($t/c \geq 0.12$) and the pitching moment must not be more severe than -0.065 ($Cm \geq -0.065$). Both constraints are applied by equally penalizing both fitness values via a linear penalty method. In addition, aerofoils generated outside the thickness bounds of 10% to 15% are rejected immediately, before analysis.

4. Solver

We utilise the XFOIL software. It comprises a higher order panel method with coupled integral boundary layer. In all cases in these studies we have allowed free transition points for the boundary layer. Because some candidates may in fact cause locally sonic flow (transonic aero foils) these will not be properly resolved by a panel method. To prevent this situation, we calculate the sonic pressure coefficient Cp^* from:

$$C_P^{\ *} = \frac{2}{\gamma M_\infty^{\ 2}}\left\{\left[\frac{1+\frac{1}{2}(\gamma-1)M_\infty^{\ 2}}{1+\frac{1}{2}(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}} - 1\right\} \tag{3}$$

Where $\gamma = 1.4$ for air, and $M\infty$ is the free stream Mach number. We examine all the reported surface C_{pi} values, and if any are found to exceed the sonic value ($C_{pi} < C_p^{\ *}$) then the candidate is rejected immediately. Also, any candidate which fails to converge the boundary layer solution is also rejected without further consideration.

5. Implementation

The optimizer is configured hierarchically with the following settings:
Top Layer: A population size of 20, 119 panels used by the solver.
Middle Layer: A population size of 20, 99 panels used by the solver.
Bottom Layer: A population size of 10, 79 panels used by the solver.

6. Results

This case was run for 5300 function evaluations of the head node, and took approximately four hours on a single 1.0 GHz processor. The resulting Pareto set is shown in Figure 6. The aerofoils comprising the Pareto front are shown in Figure 7. It can be seen that classical aerodynamic shapes have been evolved, even considering that the optimization was started completely from random and the evolution algorithm had no problem specific knowledge of appropriate solution types. We select three aerofoils for consideration from the Pareto front of 20 members (numbers 2, 10 and 20) to illustrate the two objective extremes and compromise geometry. Figure 8 shows an objective one optimal aerofoil in the transit flow regime, and it can be seen that it has evolved a conventional low-drag pressure distribution and overall form. Figure 9 and 10 show a compromise aerofoil, having a very pronounced S-shaped camber distribution. The pressure distribution is again seen to be relatively conventional, with a marked favourable gradient on the lower surface in both flow regimes. Figure 11 shows the objective two optimal aerofoil in the loiter regime, and finally it can be seen that the pressure distribution is of the classical 'rooftop' type on the upper surface while having an almost constant favourable pressure gradient on the lower surface.

Concluding this case, it is observed that all aerofoils easily satisfy the design constraints. Without any problem specific knowledge, the method has discovered forms (Figure 8 and 11) that would have been designed by an expert in aerodynamics, as well as an unusual but effective compromise form (Figure 9 and 10).

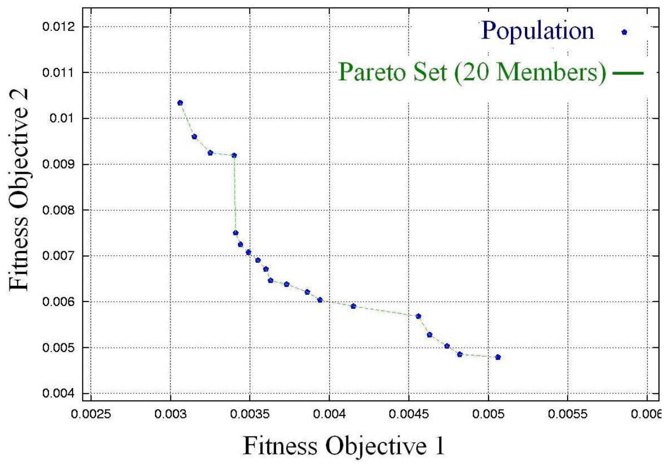

Figure 6. Pareto Front for Aerofoil Design.

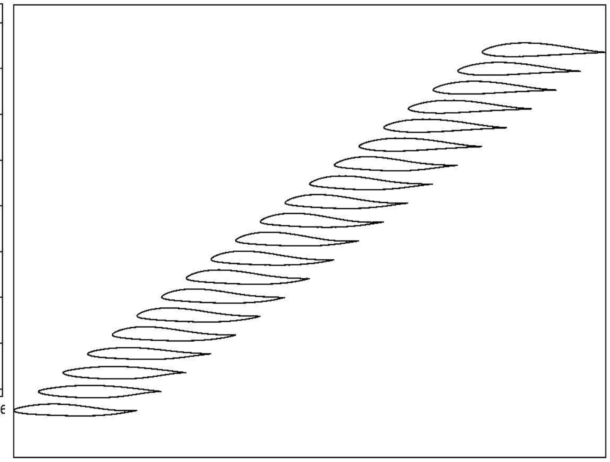

Figure 7. The Ensemble of Pareto Aerofoils.

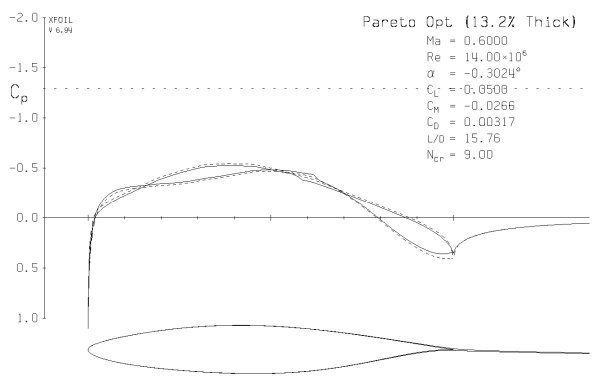

Figure 8. Objective One Optimal Aerofoil - Cruise C_P Distribution.

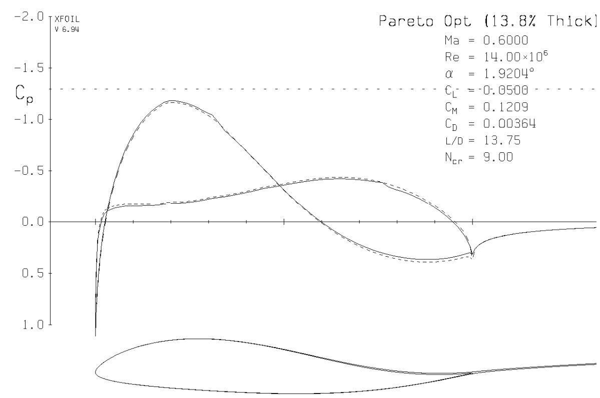

Figure 9. Compromise Aerofoil - Cruise C_P Distribution.

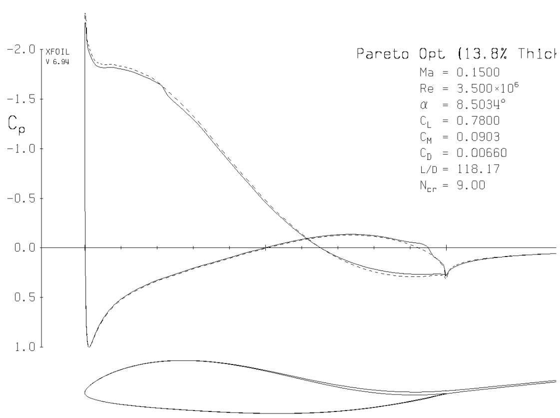

Figure 10. Compromise Aerofoil - Loiter C_P Distribution

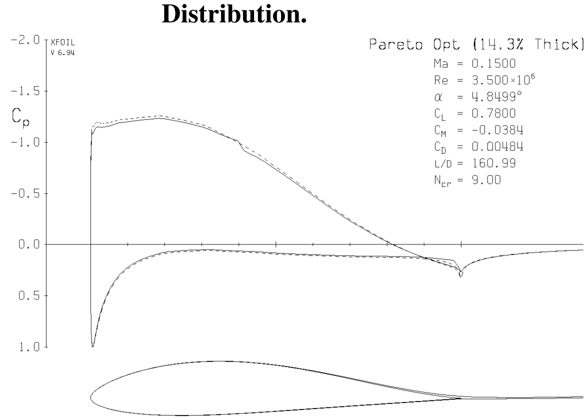

Figure 11. Objective Two Optimal Loiter C_P Distribution

B. Two Objective UAV Aerofoil Section Optimization: A Constraints Definition Study

1. Problem Definition

In this case, we consider the detailed design of a single element aerofoil for a small UAV application similar to the RQ-7A Shadow 200 Tactical UAV and use the aerofoil design module for this task. The aircraft maximum gross weight is approximately 320 *Lbs*, it has a wingspan of approximately 12.8 *ft*, a mean chord of approximately 2 *ft,* length of 11 *ft,* and a planform shape without sweep. We assume the aircraft operating between a slow cruise 33.3 *m/s* and fast cruise 46.6 *m/s* approximately. This result in the airframe, flight parameters and operating conditions indicated in table 1. These conditions assume an aircraft at mid weight-cruise during and extended cruise phase at intermediate altitude.

Table 1. UAV Data and Operating Conditions

Aerofoil section	NACA4415
Wingspan, *ft*	12.8
Wing chord (aprox), *ft*	2.0
Length, *ft*	11.2
Cruising altitude, *m*	3000

Description	Flight Condition One – Slow Cruise	Flight Condition Two – Fast Cruise
Mach	0.1025	0.141
Reynolds	1.085×10^6	1.490×10^6
C_l	1.18	0.6140

2. Analysis and Design Rationale

For the optimization, we initially assume an existing aerofoil geometry operating at two suggested design points, and then design and aerofoil that preserves the original thickness while reducing the drag coefficient. The assumed baseline aerofoil geometry is the *NACA4415*. This aerofoil is *15%* thick. Figures 12 and 13 show the pressure coefficient (*Cp*) distribution and some aerodynamic data for the two flight conditions considered. The combined polars for the NACA4415 aerofoil are shown in Figure 14. It is noted that both cruise points operate inside the invariant drag region of the aerofoil; the low speed cruise condition giving approximately $C_d = 0.016$ and the high speed giving approximately $Cd = 0.012$.

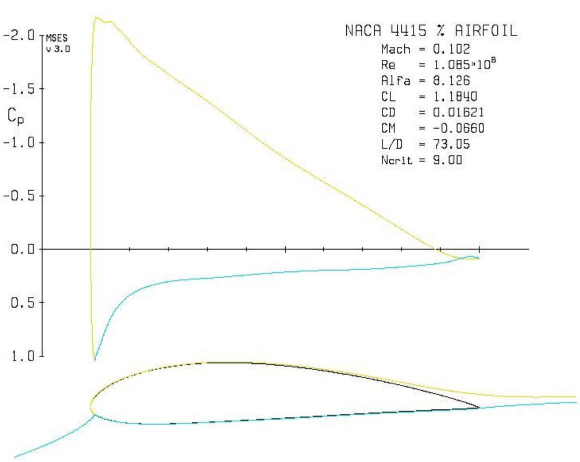

Figure 12. NACA 4415 - Flight Condition One — Slow Cruise.

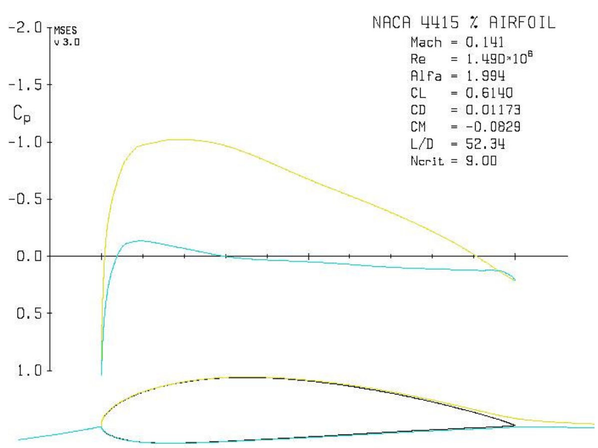

Figure 13. NACA 4415 - Flight Condition Two — Fast Cruise.

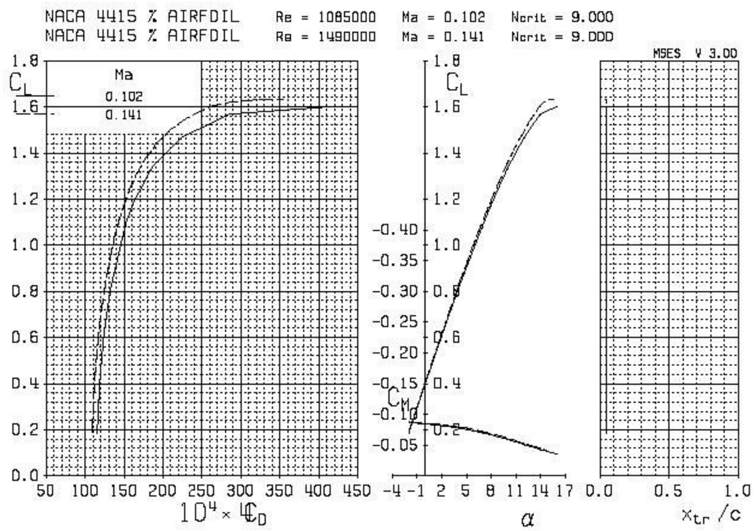

Figure 14. NACA 4415 - Polar

3. *Design and Optimisation Rationale*

In designing a replacement aerofoil for this UAV platform, the following design factors are considered:

- Maintain approximately the same C_l so as to not impinge upon the assisted launch and landing length.
- Maintain at least the current thickness, so as not to increase the weight of the wing.
- Lower the drag at both cruise points, in a multi-objective fashion.
- Study the implication of constraining the pitching moment coefficient during the evolutionary optimisation.

4. *Design Variables*

Similar to the previous test case, the aerofoil geometry is represented by the combination of a mean line and thickness distribution. In this case we consider six free control points on the mean line and ten free control points on the thickness distribution.

5. *Fitness Functions*

The two fitness functions to be optimised are defined as minimisation of drag (C_d) at the two flight conditions.

$$\min(f_1): \quad f_1 = c_d \quad \mathrm{Re} = 1.085x10^6, \mathrm{C}_1 = 1.184 \tag{4}$$

$$\min(f_2): \quad f_2 = c_d \quad \mathrm{Re} = 1.490x10^6, \mathrm{C}_1 = 0.6140 \tag{5}$$

6. *Design Constraints*

There are three types of constraints: maximum thickness, maximum thickness location and pitching moment (C_m). The thickness and maximum thickness location of each aerofoil must exceed 15 % (*$t/c \geq 0.15$*) and be between 20 and 40% chord, respectively. If a constraint on pitching moment is applied this must not be more severe than -0.0660 (*$C_m \geq -0.0660$*). When all constraints are considered they are added up and applied by equally penalising both fitness values via a linear penalty method.

7. *Solver*

The aerodynamic characteristics of the candidate aero foils are evaluated using the *MSES* software. This solver is based on a structured quadrilateral streamline mesh which is coupled to an integral boundary layer based on a multi layer velocity profile representation. Details on *MSES* can be found in Drela[18].

8. *Implementation*

This problem was implemented using the aerofoil module; two test cases are run for comparison.

Test Case I - C_m Unconstrained: The first case considers only two constraints; minimum thickness and position of maximum thickness.

Test Case II - C_m Constrained: The second case considers the three constraints; minimum thickness, position of maximum thickness and pitching moment coefficient.

We use the same parameter settings on the evolutionary optimization algorithm for the two test cases considered:

Top Layer: A population size of 20 and a computational mesh of *215 x 36*.
Middle Layer: A population size of 20 and a computational mesh of *165 x 27*.

9. *Numerical Results*

Test Case I - C_m Unconstrained Results

This test case was run for 2000 function evaluations on the top level and took approximately 8 hours in a cluster of 4 computers. The Pareto font and ensemble plot obtained after this number of function evaluations are shown in Figure 15 and 16, respectively. From this front, we select three aerofoils, objective one optimal, objective two optimal and compromise aerofoil from the middle of the front. These geometries are shown against the NACA 4415 aerofoil in Figure 17. It is evident that the evolved aerofoils have much less camber than the original aerofoil; however the thickness for all three aerofoils has been maintained at 15%. From these results we take compromise aerofoil from the middle of the Pareto front for further evaluation. Figures 18 and 19 illustrate the pressure coefficient (*Cp*) distribution for the two operating conditions considered. It is noted that the evolved aerofoil (compromise aerofoil) has a lower C_m than the original *NACA4415* aerofoil. Figure 20 shows the comparative drag polars for $Re=1.085 \times 10^{6}$ and Figure 21 that for $Re=1.480 \times 10^{6}$.

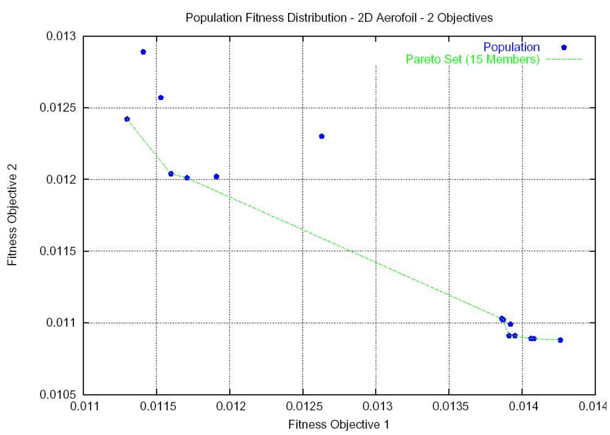

Figure 15. Pareto Front for Aerofoil Design.

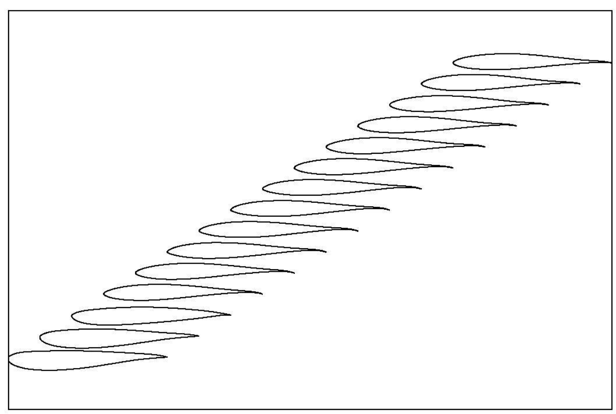

Figure 16. The Ensemble of Pareto Aerofoils.

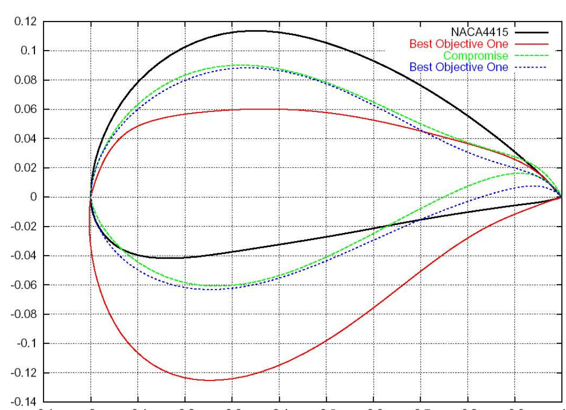

Figure 17. Comparison of selected geometries.

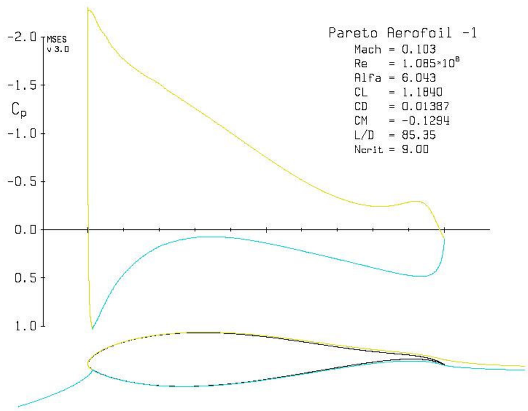

Figure 18. Pareto-01 -Flight Condition One.

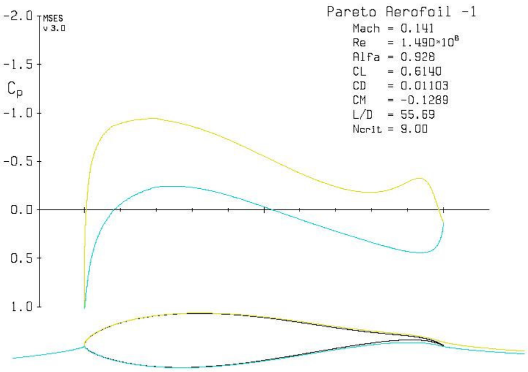

Figure 19. Pareto-01 -Flight Condition One.

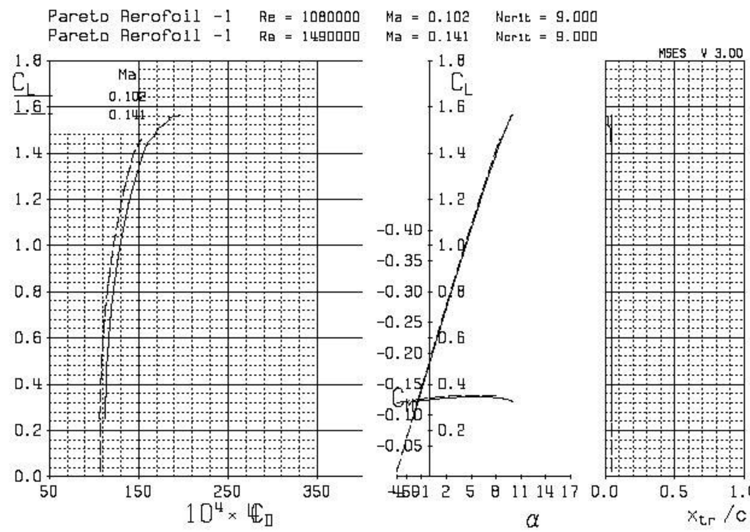

Figure 20. Comparative Polars – Compormise Aerofoil and NACA 4415 at *Re = 1.085×10⁶*.

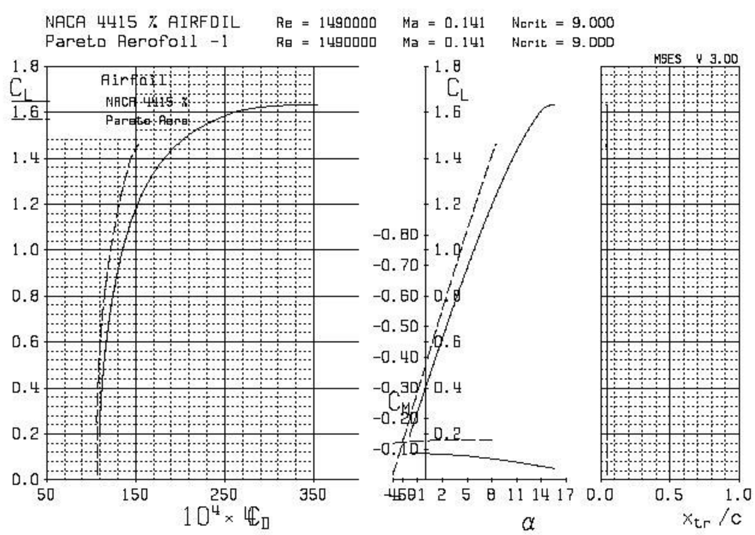

Figure 21. Comparative Polars – Compormise Aerofoil and NACA 4415 at *Re = 1.490×10⁶*.

Test Case II - Cm Constrained Results

This case was run for the same number of function evaluations and cluster of computers as in the previous test case. Figure 22 shows the ensemble of aerofoils in the Pareto front. From this front, we select three aero foils; objective one optimal, objective two optimal and compromise aerofoil from the middle of the front. These geometries are shown against the *NACA 4415* aerofoil in Figure 23. Similar to the unconstrained results we consider an aerofoil from the middle of the Pareto front for further evaluation. Figures 24 and 25 shows the *Cp* distribution for the two flight conditions. Figure 27 shows the comparative drag polars for $Re=1.480 \times 10^6$ and Figure 28 that for $Re=1.085 \times 10^6$. But in this case a lower *Cm* is obtained for both conditions. Table 2 summarizes the drag reduction at the two flight conditions for the two test cases considered.

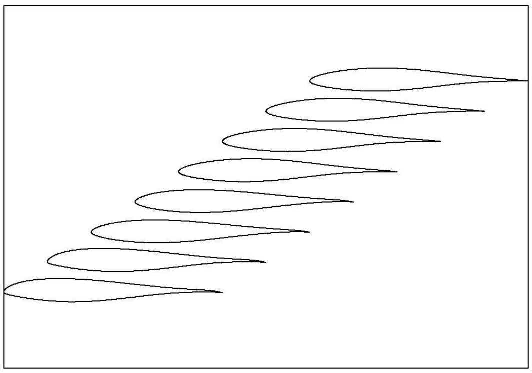

Figure 22. The Ensemble of Pareto Aerofoils. - C_m Constrained.

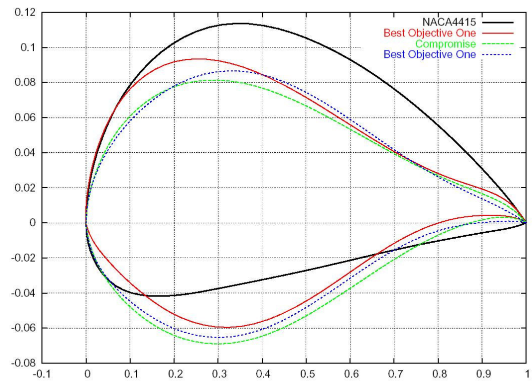

Figure 23. Comparison of selected geometries - C_m Constrained.

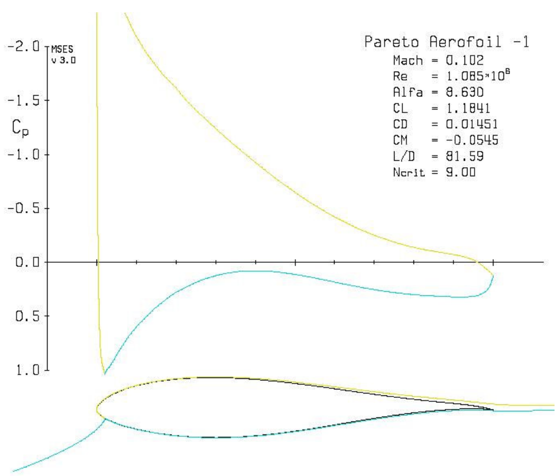

Figure 24. Pareto 01 Flight Condition One - C_m Constrained.

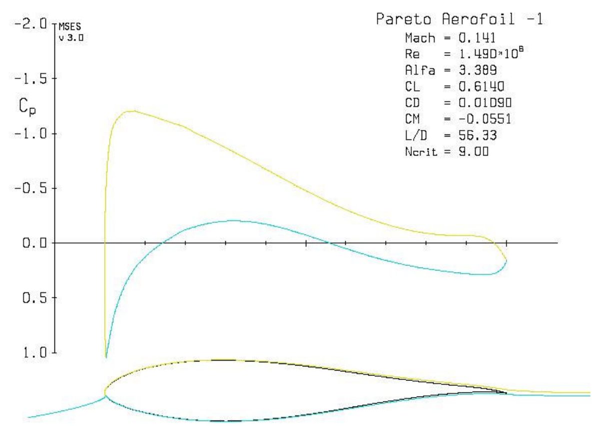

Figure 25. Pareto 01 Flight Condition Two - C_m Constrained

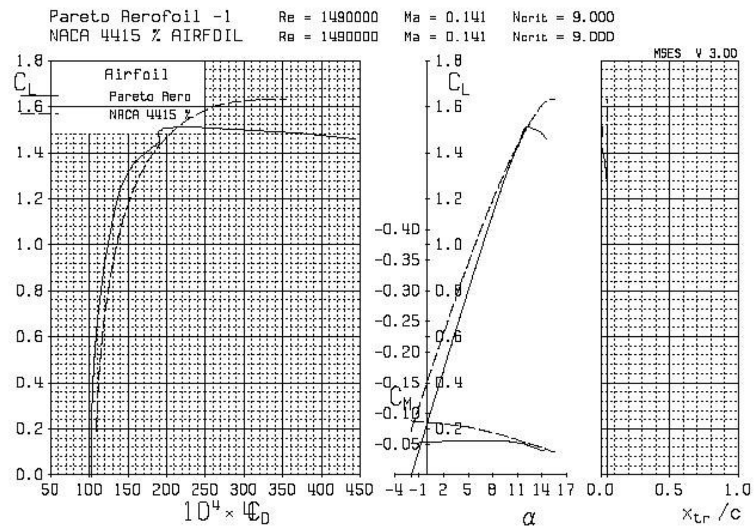

Figure 27. Comparative Polars – Compormise Aerofoil and NACA 4415
***Re=1.490 x 10^6* - C_m Constrained**

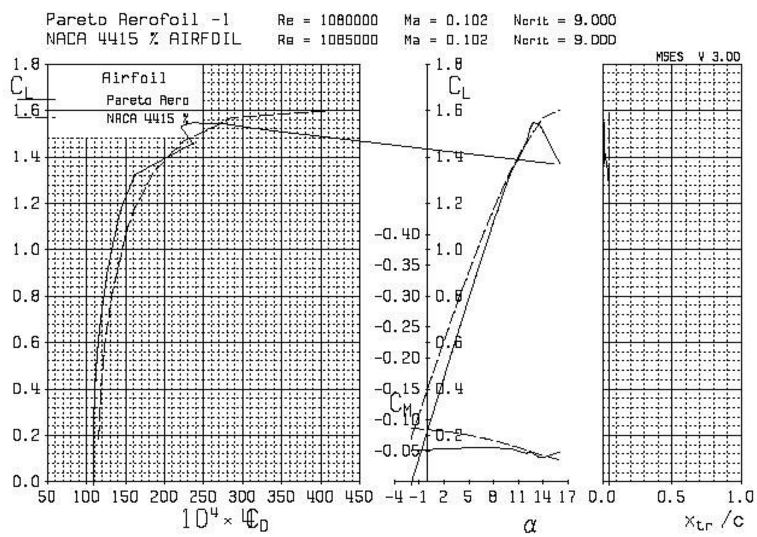

Figure 26. Comparative Polars - CompormiseAerofoil and NACA 4415
***Re=1.085 x 10^6* - C_m Constrained**

Table 1. UAV Drag reduction at two operating conditions

Description	Flight Condition One – Slow Cruise	Flight Condition Two – Fast Cruise
NACA 4415	0.01621	0.01173
Pareto 01 — C_m Unconstrained	0.01387 [-14.43 %]	0.01103 [-5.96 %]
Pareto 01 — C_m Constrained C_m	0.01451 [-10.48 %]	0.01090 [-7.07 %]

Concluding this case, it is apparent that the evolved aero foils offer significantly lower drag at both cruise conditions, but with some marked differences on their overall performance and pitching moment coefficient. While both evolved designs produced a rather constant *Cm* for increasing angle of attack, the requirement of constraining the pitching moment during the evolution process is necessary to avoid obtaining an aerofoil with lower drag for some flight conditions but with undesirable pitching moment characteristics. Concluding this case, the results obtained show the capabilities of the method to find optimal solutions and classical aerodynamic shapes for flow drag. The importance of sound engineering judgement before, during and after the optimization cannot be under-emphasized; a proper definitions of constraints before performing the evolutionary optimization and the final results need to be evaluated to obtain feasible designs.

C. Detailed Multidisciplinary Wing Design

This case considers a multi-criteria wing design optimization for a UAV. The cruise Mach number and altitude are 0.69 and 10000 *ft*. The wing area is set to 2.94 m^2 and the corresponding C_L is fixed at 0.19. For the solution we initially compute the pressure distribution over the wing using a potential flow solver to obtain the wing aerodynamics characteristics that include the span wise pressure distribution, C_L and total drag coefficients C_{Dw}. Concentrated loads replace the lift distribution and the spar cap area is calculated to resist the bending moment. The weight is then approximated as the sum of the span-wise cap weight. The strong interaction between the aerodynamic pressure distribution and the structural deflections is ignored.

1. Design Variables and Constraints.

The wing geometry is represented by three aerofoil sections and five variables for the wing planform. In total fifty-three design variables are used for the optimization. Figure 28 illustrates the main design variables and table 3 indicates their upper and lower bounds for the wing plan form. The aerofoil geometry is represented by six free control points on the mean line and ten free control points on the thickness distribution.

Constraints are imposed on minimum thickness ($t/c \geq 0.14$ root aerofoil, 0.12 intermediate aerofoil, and 0.11 tip aerofoil) and position of maximum thickness. ($20\% \leq t/c \leq 55\%$). If any of these constraints is violated both fitness are linearly penalized to ensure an unbiased Pareto set.

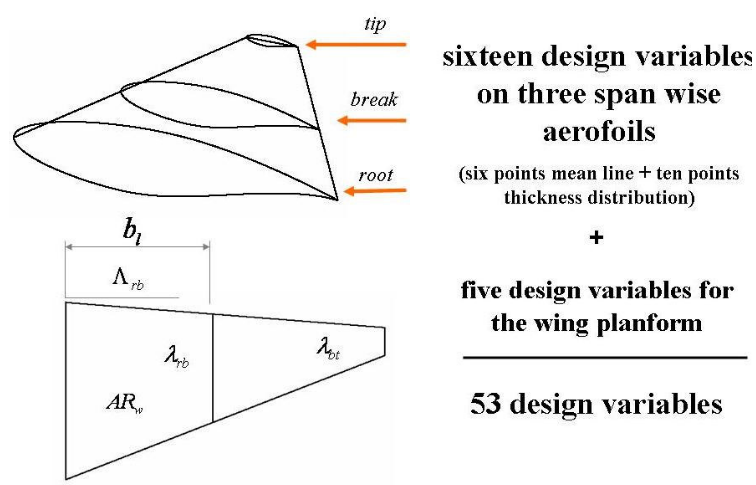

Figure 28. Design variables for multidisciplinary wing design.

2. Aerodynamics and Weight Analysis

The aerodynamic characteristics of the wing configurations are evaluated using FLO22, a 3-D full potential wing analysis software. This program uses sheared parabolic coordinates and accounts for wave drag[31]. FLO22 was developed by Jameson and Caughey for analysing inviscid, isentropic, transonic shocked flow past 3-D swept wing configurations. The algorithm is based on free stream Mach numbers limited by the isentropic assumption and weak shock waves are automatically captured wherever they occur in the flow. Also the finite difference form of the full equation for the velocity potential is solved by a relaxation method, after the flow exterior to the aerofoil is mapped to the upper half plane.

Table 3. Upper and lower bounds for multidisciplinary wing design variables

Description	Lower Bound	Upper Bound
Wing aspect ratio, [AR]	3.50	15.00
Taper ratio root to break, [λbr]	0.65	0.80
Taper ratio break to tip, [λbt]	0.20	0.45
Wing 1/4 chord sweep, *deg* [Λi]	10.00	25.00
Break location, [b_l]	0.30	0.45

The mapping procedure allows exact satisfaction of the boundary conditions and use of transonic free stream velocities. Details on the formulation and implementation can be found in Jameson et al[31].

The fixed lift requirement can be satisfied by performing an extra two function evaluations by varying the angle of attack at the wing root and assuming a linear variation of the lift coefficient. The lift distribution is summed into concentrated loads. The wing weight is estimated from the wing spar cap area designed to resist the bending moment. The local stress has to be less than the ultimate tensile stress in this case for Aluminium Alloy 2024 -T6 $\leq \sigma_{adm}$.

3. Fitness Functions

The two fitness functions to be optimized are defined as minimization of wave drag (C_{Dw}) and minimization of the sum of the span wise cap weight (W_{sc}) to resist the bending moment.

$$\min(f_1): \quad f_1 = c_{Dwave} \tag{6}$$

$$\min(f_2): \quad f_1 = \sum W_{SC} \tag{7}$$

4. Implementation

We use the wing design and optimization module to solve this problem and considered two approaches for the solution; in the first approach the optimizer is configured as a traditional EA with a single population model and computational mesh of *96 x 12 x 16* for the FLO22 code. The second approach uses a hierarchical topology of resolutions with the following settings:

Top Layer: A population size of 30 and a computational mesh of *96 x 12 x 16.*
Middle Layer: A population size of 30 and a computational mesh of *72 x 9 x 12*.

5. Numerical Results

The algorithm was run five times for 2000 function evaluations and took in average six hours to compute. Figure 29 shows the Pareto fronts obtained by using the two approaches. It can be seen how the optimization technique gives a uniformly distributed front in both cases. By inspection we can see that the use of a hierarchical approach gives an overall lower front as compared to a single model approach. Figure 30 illustrates the Pareto front for the hierarchical approach and a representative top view of the wing geometries. Figure 31 shows the corresponding aero foils at root, break and tip for some of the Pareto configurations and table 4 indicates the final values design variables.

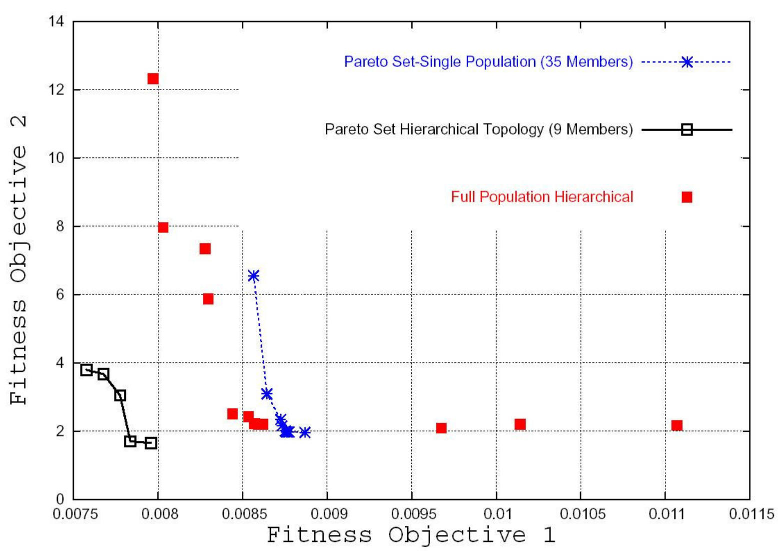

Figure 29. Pareto fronts after 2000 function evaluations.

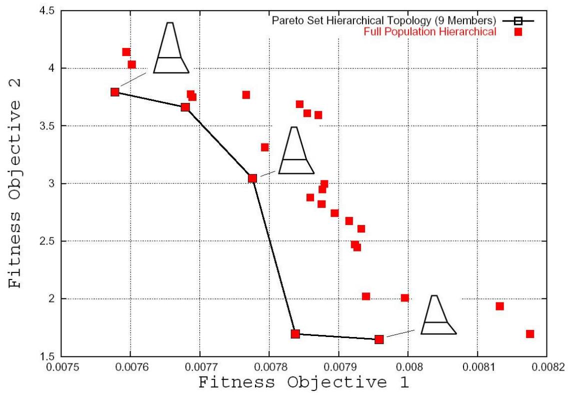

Figure 30. Pareto fronts and wing plan forms.

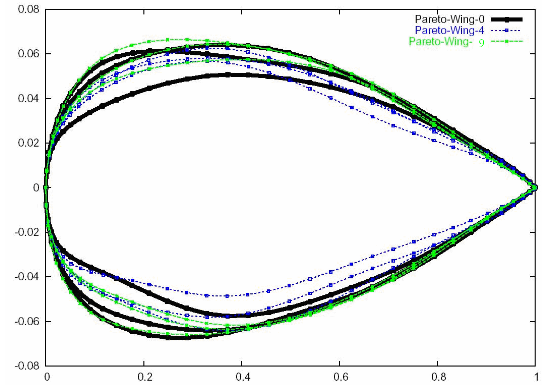

Figure 31. Aerofoil geometries at root, break and tip for three members of the Pareto front.

Table 4. Optimum design variables for some members of the Pareto front .

Description	Pareto Member 0	Pareto Member 4	Pareto Member 15
Wing aspect ratio [AR]	6.92	6.07	2.56
Wing 1/4 chord sweep, *deg* [Λi]	10.83	10.02	20.30
Wing semi span, *ft*	2.14	2.00	1.30
Taper ratio root to break, [λbr]	0.74	0.68	0.69
Taper ratio break to tip, [λbt]	0.31	0.24	0.35

This problem demonstrates the use the framework for UAV wing design and optimization. Results indicate a computational gain on using a hierarchical topology of fidelity models as compared to a single model during the optimization. Results also show how the algorithm was capable of identifying the trade-off between the multi-physics involved and provide classical aerodynamic shapes as well as alternative configurations from which the design team can choose and proceed into more detailed phases of the design process.

VI. Conclusions

This paper presented the requirements, formulation and implementation of a robust framework in which different aeronautical problems can be handled by designers with flexibility. The paper provides the designer with a brief description of the different components of the framework. These include several algorithms, a GUI and different modules for design, optimisation, mesh generation, post-processing and parallel computing capabilities. Hence we have within the framework, a complete set of numerical and aerodynamic tools for handling generic test cases and real world/UAV problems. The application of the methodology is illustrated on UAV multi-criteria problems. The robust EAs methodology used for the capture of different Pareto fronts (convex, concave or discontinuous) is capable of identifying the trade-off between the multi-physics involved and provides classical aerodynamic shapes as well as alternative configurations from which a design team can choose. There is also a significant computational gain on using a hierarchical topology of fidelity models as compared to a single model during the optimization process. As developed, the framework is comparatively easy with respect to gradient based deterministic approaches to setup and only requires 'payoff' information from the solver used. The benefits of using the framework to provide solutions for single and multi-criteria problems in aircraft/UAV design are straightforwardly identified from the numerical experiments and obtained results. Further work using higher fidelity Navier-Stokes turbulent flow analysers using adapted unstructured meshes and application of the method to more complex geometries like high lift multi element configurations are presently under investigation.

VII. Acknowledgements

The authors gratefully acknowledge Mourad Sefrioui, Dassault Aviation for fruitful discussions on Hierarchical Eas. Steve Armfield the University of Sydney for allowing access to the cluster of computers. Arnie McCullers NASA LaRC who kindly provided the *FLOPS* software, M. Drela MIT for providing the *XFOIL* and *MSES* design

software and A. Jameson, Stanford University and S. Obayashi, Tohoku University for the use of the *FLO22* software to provide the full potential flow analysis around a wing.

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